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TITLE MAGNETOPAUSE STRUCTURE AND DYNAMICS: ISSUES FOR GEM

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MASTER

Magnetopause Structure and Dynamics: Issues for GEM

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Recent multi-spacecraft observations of the magnetopause have allowed us to establish its structure and dynamical behavior. The magnetopause current sheet is thicker than expected, often ten magnetosheath ion gyroradii or more. One very important result has been the confirmation of magnetic reconnection in both its quasi-steady and transient forms. A boundary layer of magnetosheath-like plasma is often, but not always, observed earthward of the magnetopause current layer. There is considerable small-scale magnetic structure within the current layer, suggesting the presence of filamentary currents much smaller than an ion gyroradius. Such micro-structure may be important in particle diffusion and, hence, reconnection. There are many outstanding questions, among them: How does the low latitude boundary layer form? Why is the magnetopause current layer so thick? What is the detailed structure and topology of FTEs? How are quasi-steady and transient reconnection related? The GEM program may help us address these issues.

Introduction

The nature of the boundary between the Earth's magnetic field and the solar plasma has long been a subject of intense interest. *Chapman and Ferraro* [1931] recognized that plasma from the sun could dramatically influence the terrestrial environment. *Dungey* [1961] pointed out that the solar magnetic field would play an important role in the interaction, and introduced magnetic reconnection as an energy transfer mechanism between the solar wind and the magnetosphere.

Early space missions confirmed the existence of the magnetopause, but the boundary's detailed structure remained uncertain because of the spatial/temporal ambiguity inherent in single spacecraft observations. Consequently such fundamental properties as magnetopause thickness length scale and characteristic speed were very uncertain. The launch of multi-spacecraft missions such as ISEE and AMPTE brought us new understanding of the boundary, but raised new questions. Some of these questions can only be answered when new missions such as CLUSTER and ISTP are launched. But others can still be addressed with data from past and present missions, or with advances in theory and simulation.

In this paper we will review just a few aspects of our new-found knowledge of the magnetopause, and pose some outstanding questions. First, the topic of expected and observed magnetopause thickness and motion is explored. We next discuss magnetopause micro-structure, and show evidence for filamentary magnetopause currents of order 10 km in size. We discuss observations of quasi-steady and transient reconnection (FTEs), and ponder the relationship between the two. Finally, we discuss how GEM can address some of the outstanding questions related to these magnetopause phenomena.

Magnetopause Current Sheet Structure

Magnetopause Thickness

Ferraro [1952] first considered the formation of a boundary between the geomagnetic field and streams of solar plasma impinging on it. He envisaged the magnetopause as a thin layer formed by the penetration of a beam of solar ions and electrons into the geomagnetic field. The deeper penetration of the massive ions creates a polarization electric field normal to the boundary, retarding the ions and accelerating the electrons. This process is shown schematically in the upper panel of Figure 1, taken from *Willis* [1971]. The resulting current sheet thickness would be on the order of the electron inertial length, for typical conditions no more than a few kilometers. *Parker* [1967] showed that ambient particles from the ionosphere could in effect short out the polarization field, allowing magnetosheath ions to penetrate into the geomagnetic field up to one or two ion gyroradii, a distance of about 100 km. This is shown in the lower panel of Figure 1. Early estimates of magnetopause thickness based on single spacecraft data hinted that the current sheet thickness is indeed larger than the electron skin depth.

The International Sun-Earth Explorer mission was aimed at resolving the boundary thickness through use of two point observations. Calculated magnetopause thicknesses of more than 500 km were obtained [*Russell and Elphic*, 1978]. In a more comprehensive survey, *Berchem* [1984] determined that the current sheet scale length ranges between 500 and 1500 km, corresponding to many ion gyroradii. This is shown in Figure 2, where the calculated magnetopause thickness is plotted against the gyroradius of protons at local magnetosheath energies. The dashed lines represent thicknesses corresponding to 5, 10, 20 and 40 ion gyroradii. Most cases are at least ten gyroradii thick; none is less than five. This surprisingly thick current sheet implies that particles may be quasi-trapped, drifting for many gyroperiods within the boundary before escaping. *Berchem* [1984] found that the only parameter that organizes the magnetopause thickness is dipole latitude, thinner boundaries being found at lower latitudes.

Magnetopause Micro-structure

While the magnetopause current sheet thickness is typically many ion gyroradii, there is evidence of considerable small-scale structure within the boundary, suggesting the presence of filamentary or time-varying currents. Such small-scale structure can be responsible for disrupting the ideal drift motion of particles within the current sheet layer, thus leading to the breakdown of the boundary as a tangential discontinuity. We examine here some of the evidence for small-scale structure within and near the magnetopause.

The upper panel of Figure 3 shows high resolution (4 samples/s) magnetic field data from ISEE 1 near 2300 UT on November 12, 1977, when the spacecraft were inbound near the magnetopause. The data are shown in boundary normal coordinates (cf. *Russell and Elphic*, [1978]), and illustrate a rapid multiple crossing of the magnetopause at a location of (8.5, -1.9, 3.7) R_E GSM. The magnetosheath field has a southward orientation at this time. What makes these observations remarkable is that ISEE 1 and 2 are separated by only 15 km during the pass. As a consequence, if there are any significant differences in the magnetic field observed at the two spacecraft, they must be due to local currents with scale sizes of order 10's of km. The lower panel of Figure 3 shows the difference field, ISEE 1 minus ISEE 2. The difference field is small and very quiet within the magnetsphere, but noisy within the magnetopause current layer.

Figure 4 focuses on the four minutes surrounding the magnetopause crossings. At 2257 UT the spacecraft are in the magnetosphere, and enter the boundary just before 2258 UT; by 2258:35 UT the spacecraft are on the magnetosheath side of the magnetopause. They then re-enter, and remain in the boundary layer until 2300:30 UT. One striking feature in the difference field occurs during the main current sheet crossings at 2258:28 and 2258:57 UT, namely the 10 nT ΔB_L signatures which persist for roughly ten seconds. These are signatures of the Chapman-Ferraro current. The relatively steady 10 nT difference in B_L over the 10 km normal separation implies that a main current sheet thickness of about 100 km is required to accomplish the roughly 100 nT of total B_L field change between the magnetosheath and magnetosphere. Defined in this way, the current sheet thickness here is smaller than those found by *Berchem* [1984].

Of special note are the brief, spikey excursions with peak-to-peak amplitudes of up to 20 nT in all components. These very brief fluctuations in the difference field approach almost half the instantaneous background field, and they suggest the presence of small-scale current structure within the main magnetopause current sheet. If the currents were in the form of thin sheets lying parallel to the main magnetopause plane, only variations in ΔB_L and ΔB_M would result. That these fluctuations are seen in ΔB_N as well indicates the currents may have a filamentary form. It requires more than just two spacecraft to completely specify the nature of a three-dimensional current, whether it be due to intrinsic structure or a propagating wave. In any case, however, the small-scale structure in the magnetopause may play an important role in the chaotization of particle gyro orbits, and hence in particle diffusion and ultimately in the onset of reconnection.

Reconnection and FTEs

Quasi-Steady Reconnection

Fast plasma observations from ISEE 1 and 2 provided the first convincing in situ evidence for quasi-steady-state reconnection at the magnetopause. *Sonnerup et al.* [1981] showed that the accelerated plasma flow in the magnetopause is consistent with the expected stress balance of quasi-steady reconnection, and that the process can persist in time over many minutes. This can be seen in Figure 4, showing plasma and magnetic field data from ISEE 1 and 2 for September 8, 1978. The satellites are separated by about 1800 km, with ISEE 2 leading outbound. On this pass the magnetopause was observed at a radial distance of about 8.5 R_E, at 1140 hours LT and +26 degrees latitude.

ISEE 2 is the first to encounter rapidly flowing plasma in the boundary layer and then in the magnetopause current sheet itself at 0038 UT. When ISEE 1 enters the boundary region at 0041 UT it too observes accelerated plasma flows with magnitudes greater than 400 km/s. As ISEE 1 exits the magnetopause current sheet, the flow speed drops to background magnetosheath values of 100 km/s or less. Then, at 0046 UT, high speed flows again are seen in concert with a partial entry into the magnetopause. At ISEE 2 in the magnetosheath further from the boundary no accelerated plasma flow is seen, although fluxes of more energetic ring current particles are seen.

The accelerated plasma flows observed here agree quantitatively with those expected of reconnection. But while these flows are quasi-steady on a time scale of a few minutes, a longer period modulation may exist. The center times of the fast flow events are 0025, 0033, 0041 and 0049 UT, suggesting a recurrence time scale in this case of about 8 minutes. While this behavior could conceivably be due to radial motion of the boundary, it could as well be evidence of the basic transient nature of the reconnection process, a transient aspect that has been used to explain FTEs.

Flux Transfer Events: Morphology and Phenomenology

There is considerable evidence that FTEs are the result of impulsive reconnection at the magnetopause. Their magnetic signature implies that they are not simple surface waves on the magnetopause. They are sometimes associated with accelerated plasma flows with speeds very much higher than the magnetosheath flow speed. They are associated with electron heat flux, and energetic particle data support the idea that they contain open field lines. FTEs appear to occur almost exclusively when the IMF is southward [*Berchem*, 1984].

There is an extremely important note to FTE observations: Not everyone appreciates that many FTEs, at least as seen in magnetic field data, are not passages of the spacecraft through a reconnected flux tube. Instead the signature is often that of a grazing impact, primarily the disturbance field around the FTE axis. *Farrugia et al.* [1986] studied these signatures and showed that they are approximately consistent with incompressible plasma flow about an impenetrable cylinder. Consequently the field strength maxima so often seen in FTEs do not necessarily correspond to the core field of a twisted flux rope structure, but rather simply to the draping field around the FTE core region. In fact, such a signature is ambiguous; it could be produced by a reconnection process or by an isolated surface wave.

That FTEs are not simple surface waves on the magnetopause can be seen from their magnetic signature both inside and outside the magnetosphere. Figure 5 is a time series of the magnetic field in boundary normal coordinates for a magnetopause crossing by ISEE 2 on October 21, 1980. The spacecraft passes out of the magnetosphere into the magnetosheath, crossing the magnetopause at 1247 UT. FTEs are observed almost continuously from 1212 UT until 1326 UT. The bipolar signatures in B_N have the same +/- sense whether they are seen inside the magnetosphere, or in the magnetosheath. In order for a surface wave to produce both signatures, it must push the magnetopause only inward for magnetospheric FTEs and only outward for magnetosheath FTEs. The simpler explanation is that the FTE is a disturbance like a blister on the boundary, distorting both the southward magnetosheath and northward magnetospheric fields to produce the characteristic +/- B_N signature in the northern magnetopause and a reverse -/+ signature in the south.

Another, almost brute-force demonstration of the FTE morphology comes from simultaneous observations of the magnetic fields on either side of the magnetopause. This was possible when ISEE 1 and 2 were at their greatest separations on the dayside in 1979, with one spacecraft in the magnetosphere, the other in the magnetosheath. *Farrugia et al.* [1987] discussed these observations in detail. All the evidence points to a structure much like an elongated blister on the magnetopause, rather than a surface wave.

One open question concerning FTEs is their explicit magnetic topology, and by implication, the form of reconnection that gives rise to FTE structure. Either impulsive reconnection, as suggested by *Scholer* [1988] and *Southwood et al.* [1988], or multiple x-line reconnection [*Lee and Fu*, 1985; *Crooker* 1986] could produce the observed signatures. There are also questions concerning the role of Kelvin-Helmholtz in reconnection: *Labelle-Hamer et al.* [1988] has suggested that tearing mode may feed off the K-H instability. There is also the possibility that the reverse takes place, that strongly sheared reconnection flows could drive K-H.

FTE Quasi-periodicity and Chaos

We showed evidence earlier that even quasi-steady-state reconnection may have some intrinsic time scale for growth and decay. FTEs appear to be highly time-dependent reconnection events. Sometimes quasi-steady reconnection and FTEs are observed on the same magnetopause pass. Are the two seemingly distinct forms of reconnection related? Is there an intrinsic time scale associated with the reconnection instability?

Figure 6 shows a pass through the magnetopause near the nose by AMPTE UKS. The panels contain ion density, temperature, thermal pressure, and vector flow velocity, respectively. The bottom panels show magnetic field; both field and flow are in boundary normal coordinates. UKS is initially in the magnetosphere as evidenced by the low plasma density and high temperature; there is a brief exit to the magnetosheath between 1559 and 1602 UT, characterized by high densities and low temperatures. Thereafter UKS returns to the magnetosphere but has two encounters with boundary layer-like plasma at 1604 and 1608 UT; the satellite does not exit the magnetosphere completely until 1610 UT.

There are flow bursts throughout the pass, with center times of 1559:30, 1601:45, 1604:30, 160[illegible]:15, 1610:30, 1614:00 and 1616:30 UT. The first two and the event at 1610:30 UT are associated with magnetopause current sheet crossings, and may reflect quasi-steady reconnection. The others appear to be associated with bipolar variations in the B_N component, a signature of FTEs. All flow bursts are associated with ion thermal pressure maxima. Two possible explanations of this behavior are (1) Motions of the magnetopause, including undulations or small wavelength surface waves, carry a relatively steady-state fast flow layer over the spacecraft, giving the illusion of temporal burstiness; (2) Rapid reconnection flows occur over a variety of time scales, from quasi-steady to impulsive. In the former only quasi-steady reconnection is required, along with surface motion of the magnetopause; however, the arguments advanced in the last section put this explanation in doubt. The second picture explains why there should be a B_N signature in some events and not in others.

The quasi-periodic occurrence of reconnection events, and in particular FTEs, suggests that the process has some intrinsic time scale for the buildup and release of free energy in the magnetopause current sheet. If so, there should be a relationship between the energy released in a FTE and the free-energy buildup time: the longer the buildup time, the greater the energy available for release, and hence the greater the energy in the FTE. This process is analogous to proposed substorm mechanisms in the magnetotail, to the unsteady flow of water drops from a leaky faucet, and even to the occurrence of earthquakes. It is, in short, characteristic of a highly nonlinear dynamical system.

So we wish to explore the relationship between FTE (released) energy and the accumulated free energy since the last release. Because it is impossible to determine the total energy content of a FTE, we must use a measurable quantity which is in some way related to energy content. One possible parameter is simply FTE size, as characterized by the duration of the event. For this quantity to be a valid size parameter, we must assume that all FTEs travel at the same speed. To characterize the free energy accumulated at the magnetopause, we use the time since the last FTE. For this quantity to be a valid parameter we must assume that the last FTE released all free energy from the boundary, and moreover that the free energy accumulation rates are always the same.

We have measured FTE durations and inter-FTE times for events observed by AMPTE UKS or IRM and ISEE 1 and 2, these are shown in Figure 7. Two points emerge: (1) Most of the FTEs observed by AMPTE, sampled closer to the equator, have shorter durations; (2) Larger FTEs tend to be observed for longer inter-FTE times. There is considerable scatter in the data, suggesting that our assumptions are not entirely good. Another parameter relating to FTE energy content would be an estimate of FTE cross-section. A measure of the FTE extent normal to the boundary is the ratio of the bipolar B_N excursion to the background field. The larger the size of the FTE normal to the boundary compared to its extent along the boundary, the larger the value of $\delta B_N / < B >$. When multiplied by FTE duration, the quantity becomes an estimate of FTE size in the boundary normal direction. Figure 8 shows how this quantity varies with inter-FTE time. Once again there is a trend suggesting that "larger" FTEs are found after longer energy accumulation times, and most of the AMPTE FTEs are smaller than the ISEE FTEs.

There are many reasons for the scatter in Figures 7 and 8. Our simple measures of FTE size or energy content, and of the boundary's free energy accumulation time are crude. It is unlikely that all FTEs convect past the spacecraft at the same speed: the free-energy accumulation rate is likely to vary with IMF and solar wind dynamic pressure. Moreover, the quantity "Time Between FTEs" hides the fact that, if the last FTE was a small one, little free energy was removed from the boundary. Thus, a large FTE could follow a small one by a very short time.

Like unsteady water drops, there should be a relationship between the time since the last FTE and the time since the last one before that. This relationship, a kind of FTE strange attractor, would not be obvious until hundreds or thousands of FTEs had been observed, and then only under absolutely constant external conditions. In practice the external conditions are constantly changing. Thus, an intrinsically endogenic process (the quasi-periodic accumulation and shedding of free energy in the boundary) could be triggered irregularly by exogenic processes (solar wind pressure pulses, or changes in IMF orientation). A solar wind pressure pulse, for example, could pinch an initially stable magnetopause current sheet, drive it unstable, and produce a burst of reconnection.

Magnetopause Dynamics

IMF Effects

The Kelvin-Helmholtz instability has long been touted as a mechanism for the transfer of energy from the solar wind to the magnetosphere, particularly when the interplanetary field is northward. It is of interest to examine the dynamics of the magnetopause as a function of IMF orientation. *Song et al.* [1988] studied hundreds of magnetopause crossings of ISEE 1 and 2, and determined the extent of radial motion of the boundary based on the first and last crossing location. Then they catagorized these crossings as a function of local time and IMF orientation. The results are shown in Figure 9. Here is shown amplitude of the magnetopause radial motion versus solar zenith angle for crossings near the equatorial plane, for southward IMF (top panel) and for northward IMF (lower panel). The lines denote the median values in each 20 degree solar zenith angle bin.

The results show clearly that magnetopause motion is much more pronounced during southward IMF than northward. The amplitude of motion increases from less than 0.2 R_E at the nose to almost 1 R_E near the flanks. For northward IMF the typical radial amplitude is no greater than about 0.2 R_E, and if anything it decreases from the subsolar point. The northward IMF cases have many zero amplitude events, each of which corresponds to a single crossing of the magnetopause. One can infer from these results that there is no evidence for the growth of Kelvin-Helmholtz instability for northward IMF. Song et al. have shown that the average magnetopause motion during northward IMF is consistent with the typical "noise level" of solar wind dynamic pressure changes. The greater magnetopause dynamics seen for southward IMF may have their cause in reconnection-related processes. Certainly FTEs play a role in creating magnetopause disturbances of up to 0.5 R_E amplitude.

Solar Wind Transients

The foregoing results do not exclude the possibility that sudden changes in solar wind conditions can dramatically affect the magnetopause, and the polar ionosphere, when the IMF is northward. *Friis-Christiansen et al.* [1987] have studied a large twin-vortex event in the ionosphere that was clearly related to an abrupt change in solar wind dynamic pressure and IMF orientation. *Elphic* [1988] has discussed this event. In essence, any localized, travelling perturbation at the magnetopause produces a disturbance in the surrounding closed magnetospheric field lines; this disturbance is communicated to the ionosphere via Alfvén waves.

This is, in effect, a new mode of solar-terrestrial interaction. The coupling is greatest when conditions are most unsteady. In cases of northward IMF, as in the *Friis-Christiansen et al.* [1987] event, low latitude reconnection is expected to play little or no role; during such times this transient-coupling effect may be the primary mode of energy transfer from the solar wind to the magnetosphere. The boundary need not be Kelvin-Helmholtz unstable. Energy is transferred all the same.

SUMMARY AND ISSUES FOR GEM

Recent observations of the magnetopause have taught us a great deal about the large and small-scale structure and dynamics of the boundary between the solar wind and the magnetosphere. We have seen that magnetopause structure ranges from sub-gyroradius scales up to and exceeding 1 R_E. There is considerable evidence for the existence of reconnection in both its quasi-steady and transient forms. There are also important magnetopause processes associated with the unsteady solar wind, processes which have important ramifications for solar wind/ionosphere coupling.

While early theoretical predictions for the magnetopause thickness ranged from an electron inertial length up to one or two ion gyroradii, measured current sheet thicknesses from ISEE observations indicate the boundary is usually ten times this thickness, and sometimes more. There is fine structure in the current sheet, however. The cause of this small-scale filamentary structure is unknown, but it may play an important role in the scattering of particles within the magnetopause.

Observations have also established the existence of reconnection phenomena at the magnetopause. In particular, the observed accelerated plasma flow at the magnetopause is consistent with quasi-steady reconnection. Data from the widely separated spacecraft show that this process is confined to the magnetopause current layer region, can be steady on timescales of minutes but is episodic over longer periods. Another example of episodic or transient reconnection is the flux transfer event. Data from ISEE and AMPTE UKS together show that FTEs can be seen simultaneously at widely separated sites. The quasi-periodic nature of FTE occurrence suggests that the magnetopause has some intrinsic time scale for the buildup and release of free energy when the IMF is southward. This inter-FTE time scale appears to be related to the FTE energy content, or its size: the longer the time since the last FTE, the longer the FTE "growth phase", and the larger the next FTE will be.

Reconnection is just one source of magnetopause dynamics. Transient changes in solar wind dynamic pressure can lead to dramatic magnetopause dynamics, as in the case discussed by *Friis-Christiansen et al.* [1987]. Even for northward IMF orientations, significant energy transfer between the solar wind and the ionosphere can take place. This mechanism depends on variable as opposed to steady conditions for the communication of energy from the solar wind to the magnetosphere/ionosphere system.

Here are just a few of the outstanding questions that GEM can help answer:

(1) Why is the magnetopause many ion gyroradii thick? What causes the small-scale (sub-ion-gyroradius) structure within the current sheet? What process is responsible for the resistivity leading to reconnection?

Both simulations and analysis of observations may help us understand magnetopause current sheet structure. As in the study of collisionless shocks, kinetic simulations can track the microscopic processes which give rise to large scale behavior. From observations it may be possible to determine under what conditions small-scale structure appears in the current sheet, and whether or not it is associated with reconnection.

(2) What is the true topology and phenomenology of FTEs? How are FTEs and quasi-steady reconnection related?

MHD simulations provide explicit plasma and magnetic field behavior against which data can be compared. Very little rigorous quantitative testing of various FTE theories has been done using the most important discriminator of all: observations. It is equally important that we use observations to construct an empirical description of what a FTE is. Simulations may also be able to show whether or not FTEs represent a chaotic transitional state of reconnection.

(3) What is the effect of unsteady solar wind conditions? How do pressure pulses influence solar wind/magnetosphere/ionosphere coupling?

Observations suggest that variable, as opposed to steady solar wind conditions lead to an important transfer of energy from the magnetopause to the ionosphere. If possible, it is important to tie together simultaneous ground- and space-based observations to understand better this mode of coupling. Likewise, global simulations must begin to include variable upstream conditions in order to predict how IMF changes and dynamic pressure pulses map to the magnetopause, and from there to the atmosphere.

The GEM program provides an opportunity to do coordinated science focused on specific regions, processes and phenomena. It is a chance for the theorist, simulator and experimenter to work together, to advance understanding in a kind of three-way feedback process. The relevant topics range from the smallest kinetic scales to the size of the magnetosphere; there is something for everyone. If there is a danger to the GEM approach, it is that a narrow scientific focus may lack the flexibility to deal with an evolving study. The task is not to find the right answers, it is to ask the right questions.

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Figure Captions

Fig. 1. Schematic diagram of ion and electron trajectories for a beam incident on the geomagnetic field. The upper panel shows the case for a vacuum geomagnetic field: the deeper penetration of ions leads to a polarization electric field which retards ions and accelerates electrons. The current layer thickness in this case is roughly the electron inertial length, for typical conditions about 1 km. The lower panel shows the case where ambient magnetospheric (or ionospheric) particles are able to short out the polarization field. Then the current layer thickness is roughly an ion gyroradius, for typical conditions about 100 km. (From *Willis* [1971]).

Fig. 2. Magnetopause current sheet thickness as determined by ISEE 1 and 2 time-of-flight analysis, compared to the corresponding ion gyroradius based on measured fields and magnetosheath ion temperatures. The two symbols refer to ion gyroradii based on ion temperature measurements from two different instruments. Most magnetopause thicknesses are greater than ten ion gyroradii, and none are less than five. (From *Berchem* [1984]).

Fig. 3. ISEE 1 and 2 data from November 12, 1977, near a boundary crossing at 2300 UT. The data are in boundary normal coordinates. The satellites were separated by only 15 km on this day. The upper panel shows the high resolution magnetic field data from ISEE 1, the lower panel the difference field (ISEE 1 minus ISEE 2). The satellites briefly exit the magnetosphere, crossing the main magnetopause current layer twice. A ΔB of 10 nT corresponds to roughly 800 nA/m^2. The strong positive ΔB_L signature corresponds to the Chapman-Ferraro current. There is considerable small scale structure present in all three components. Within the magnetosphere proper the difference field is very small and quiet, indicating no small scale currents of any significance.

Fig. 4. Fast plasma and magnetic field data from ISEE 1 and 2 for a magnetopause crossing on September 8, 1978. Rapid plasma flows are observed in the vicinity of the magnetopause (as indicated by the change in B_Z). These flows, which are much faster than the nearby magnetosheath flows, are consistent with steady state reconnection, though they appear to occur in a semi-episodic manner. (From *Sonnerup et al.* [1981]).

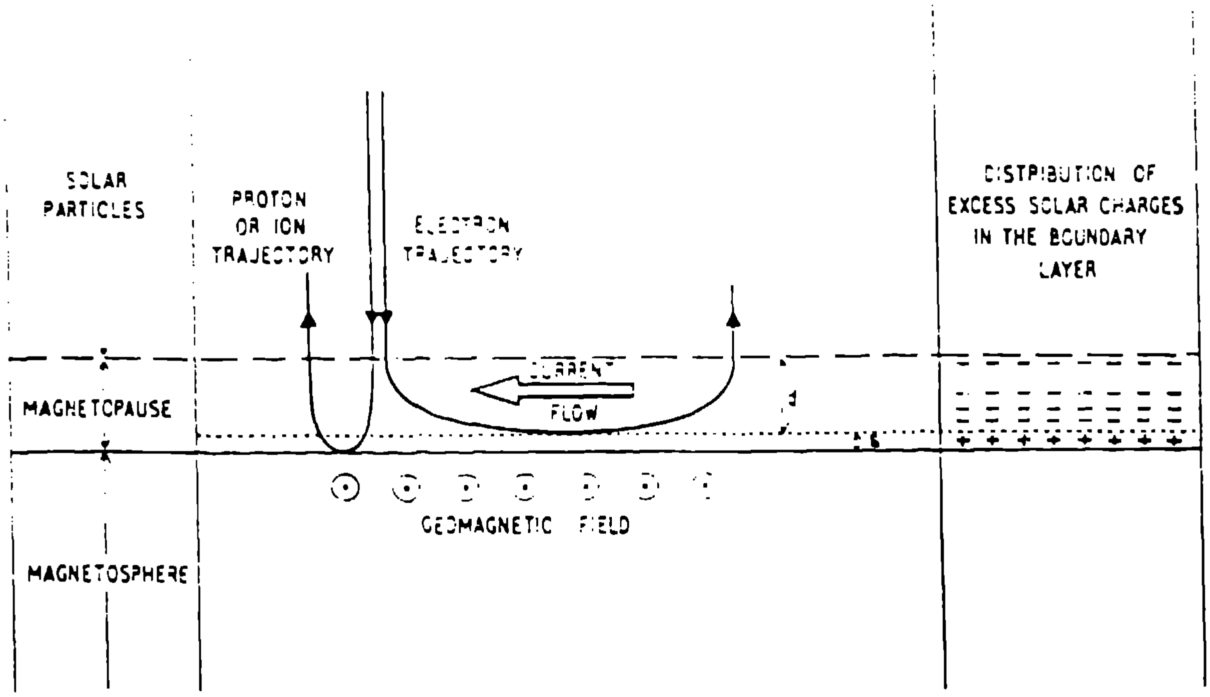
Fig. 5. ISEE 2 magnetopause and FTE observations for an outbound pass on October 21, 1980, between 1200 and 1340 UT. The data are in boundary normal coordinates. FTEs are observed both in the magnetosphere between 1210 and 1245 UT, and in the magnetosheath between 1245 and 1325 UT. The characteristic bipolar B_N signatures have the same +/- sense in both the magnetosphere and magnetosheath. Simple surface waves on the magnetopause boundary could not produce this sense of B_N on both sides of the magnetopause.

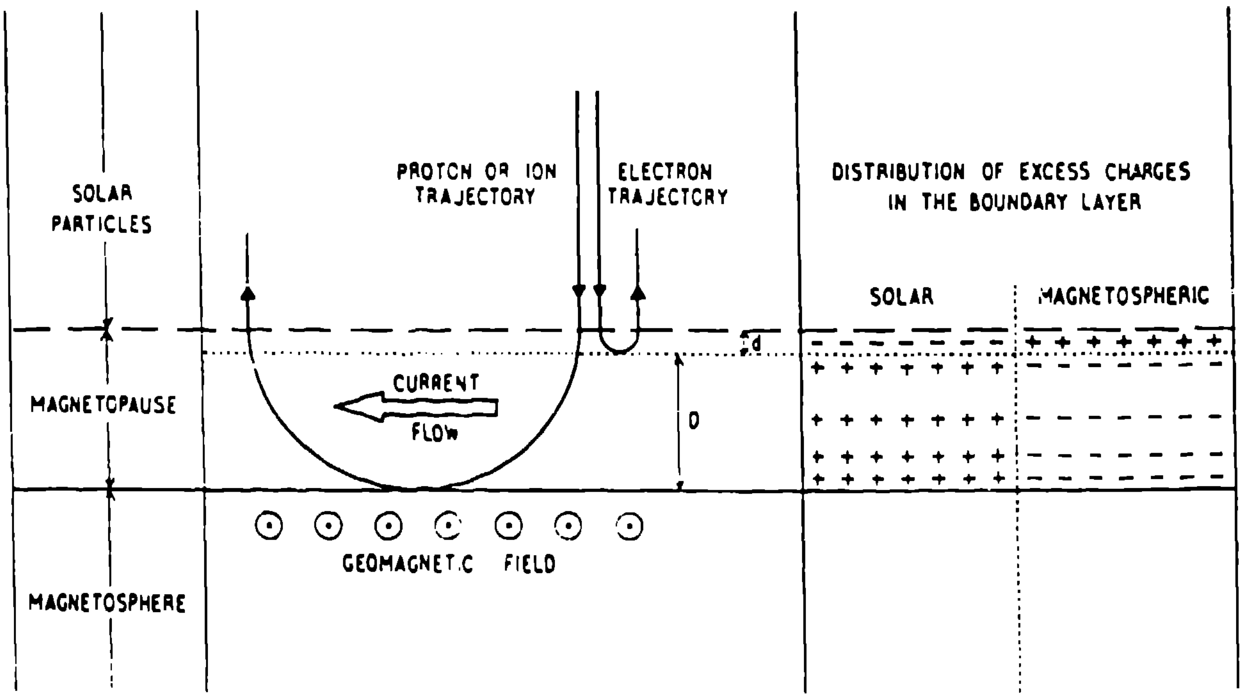
Fig. 6. Plasma ion and magnetic field data from AMPTE UKS for magnetopause crossings on September 19, 1984. The velocity and field are in boundary normal coordinates. As can be seen in the B_L component, the crossings occur at 1559:30, 1602:00 and 1611:00 UT, and accelerated flows are observed at these times. Rapid flows are also seen associated with the FTEs at 1604, 1607, 1614 and 1617 UT. Once again, the accelerated plasma flows appear to occur in a quasi-periodic manner, every 2 to 3 minutes. Each flow burst is associated with a maximum in ion thermal pressure.

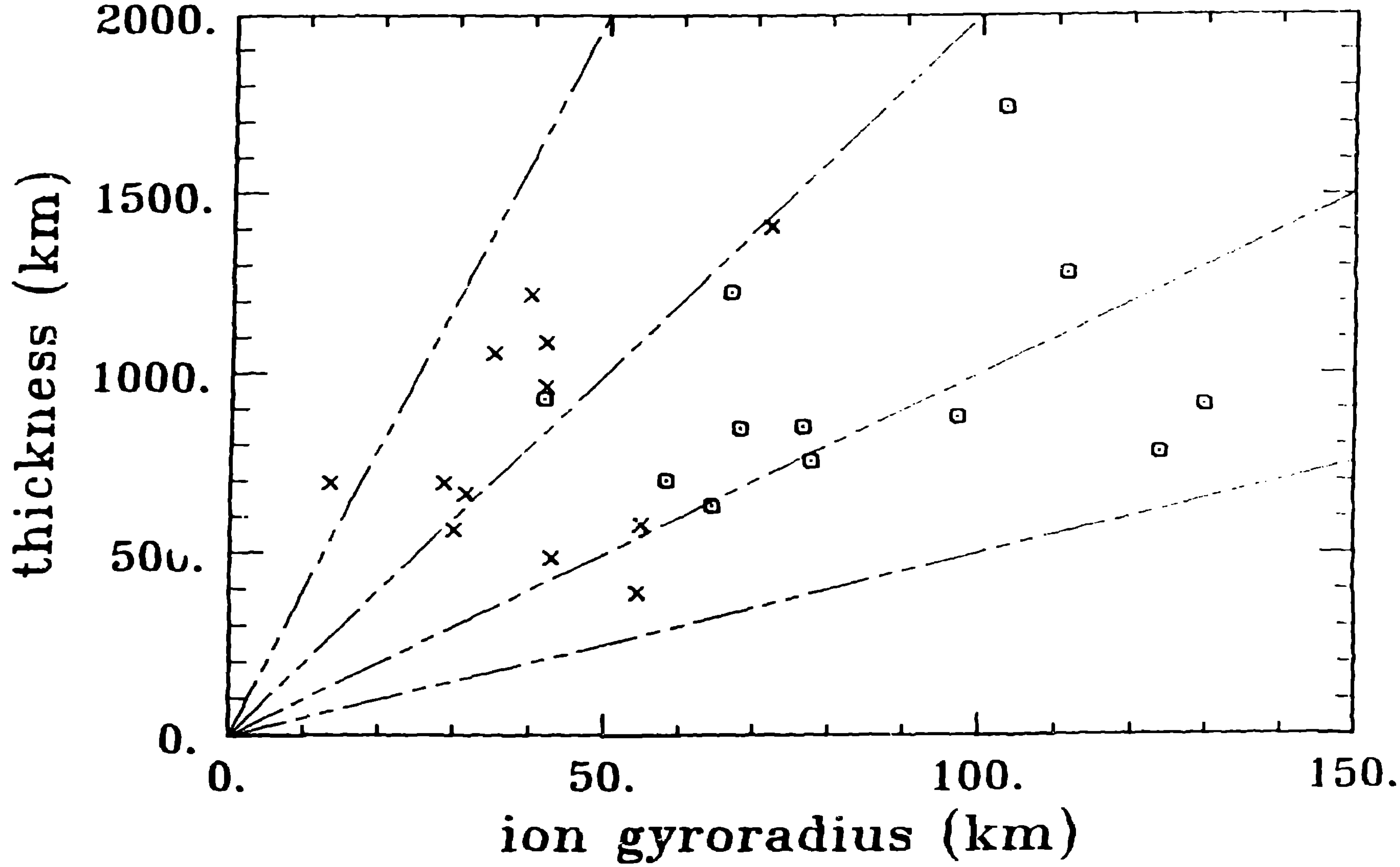
Fig. 7. FTE durations versus inter-FTE time. FTE duration is defined as the time between the extrema of the bipolar B_N signature; inter-FTE time is simply the time elapsed since the last FTE. If duration is an indication of FTE size, hence energy content, and inter-FTE time is an indicator of magnetopause free-energy accumulation time, then longer accumulation times lead to larger FTEs. Most of the AMPTE FTEs, sampled at lower latitudes, are smaller than those at ISEE.

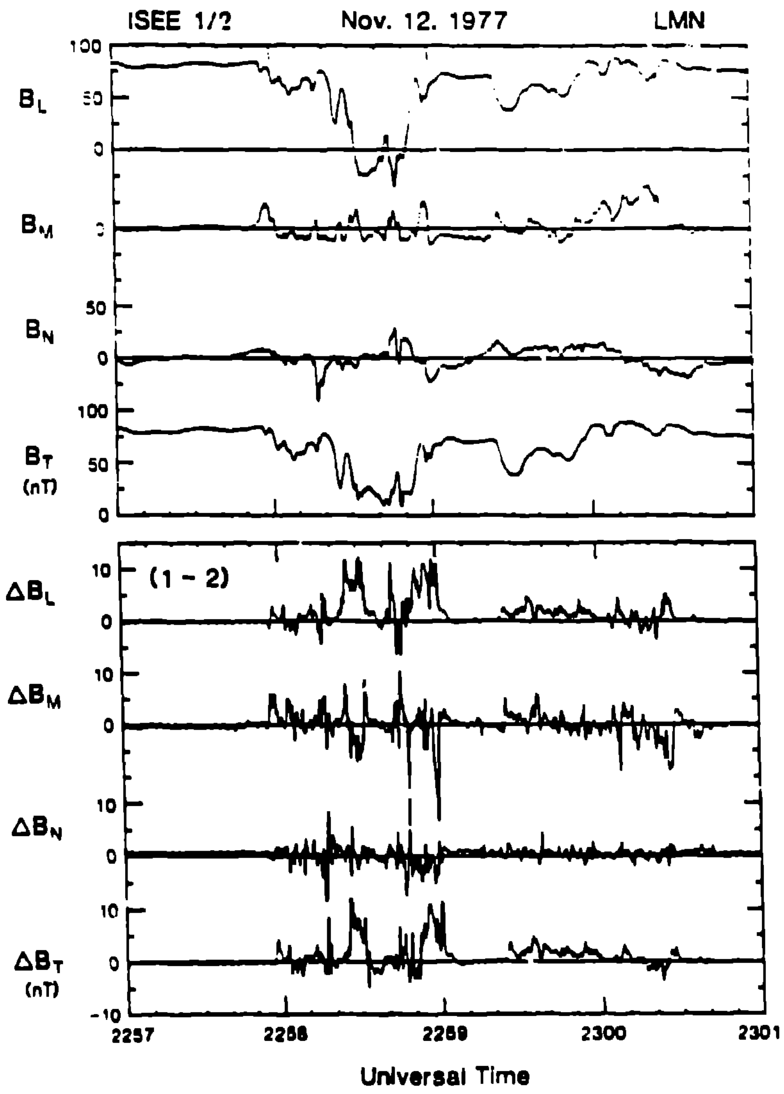
Fig. 8. Another FTE "size" measure versus inter-FTE time. The product of duration and $\delta B_N / < B >$ is a measure of FTE size normal to the magnetopause surface. Once again, larger FTEs appear to be associated with longer inter-FTE times.

Fig. 9. Amplitude of magnetopause radial motion as a function of solar zenith angle for northward (upper panel) and southward (lower panel) IMF orientations. Medians are shown by lines. The magnetopause radial amplitude is much greater for southward than for northward IMF. There is no evidence for growth of the Kelvin-Helmholtz instability during northward IMF. From *Song et al* [1988].

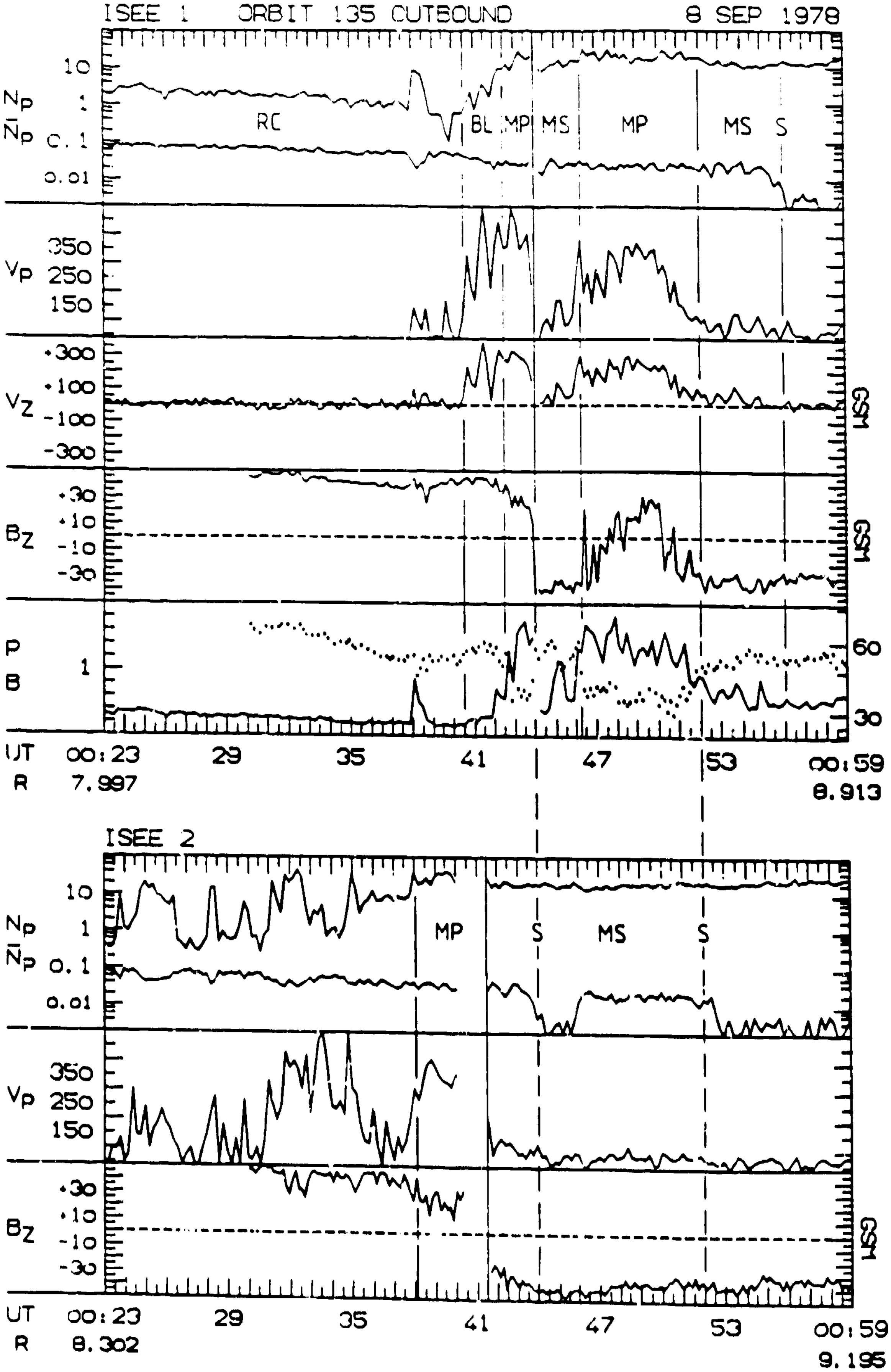

SOLAR PARTICLES
PROTON OR ION TRAJECTORY
ELECTRON TRAJECTORY
DISTRIBUTION OF EXCESS SOLAR CHARGES IN THE BOUNDARY LAYER
MAGNETOPAUSE
CURRENT FLOW
d
GEOMAGNETIC FIELD
MAGNETOSPHERE


SOLAR PARTICLES
PROTON OR ION TRAJECTORY
ELECTRON TRAJECTORY
DISTRIBUTION OF EXCESS CHARGES IN THE BOUNDARY LAYER
SOLAR
MAGNETOSPHERIC
d
MAGNETOPAUSE
CURRENT FLOW
D
GEOMAGNETIC FIELD
MAGNETOSPHERE

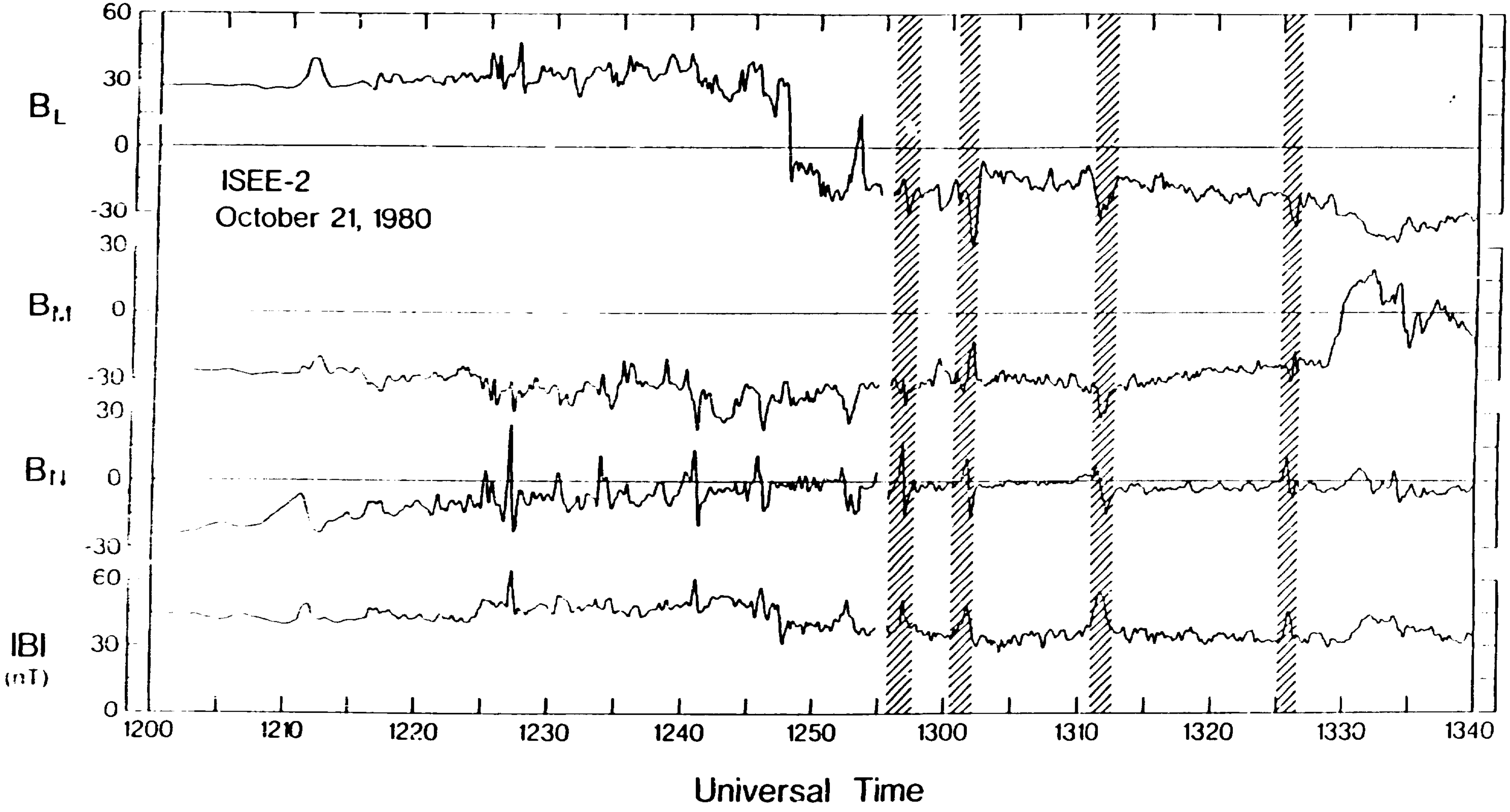

2000.
1500.
1000.
500.
0.
thickness (km)
0.
50.
100.
150.
ion gyroradius (km)



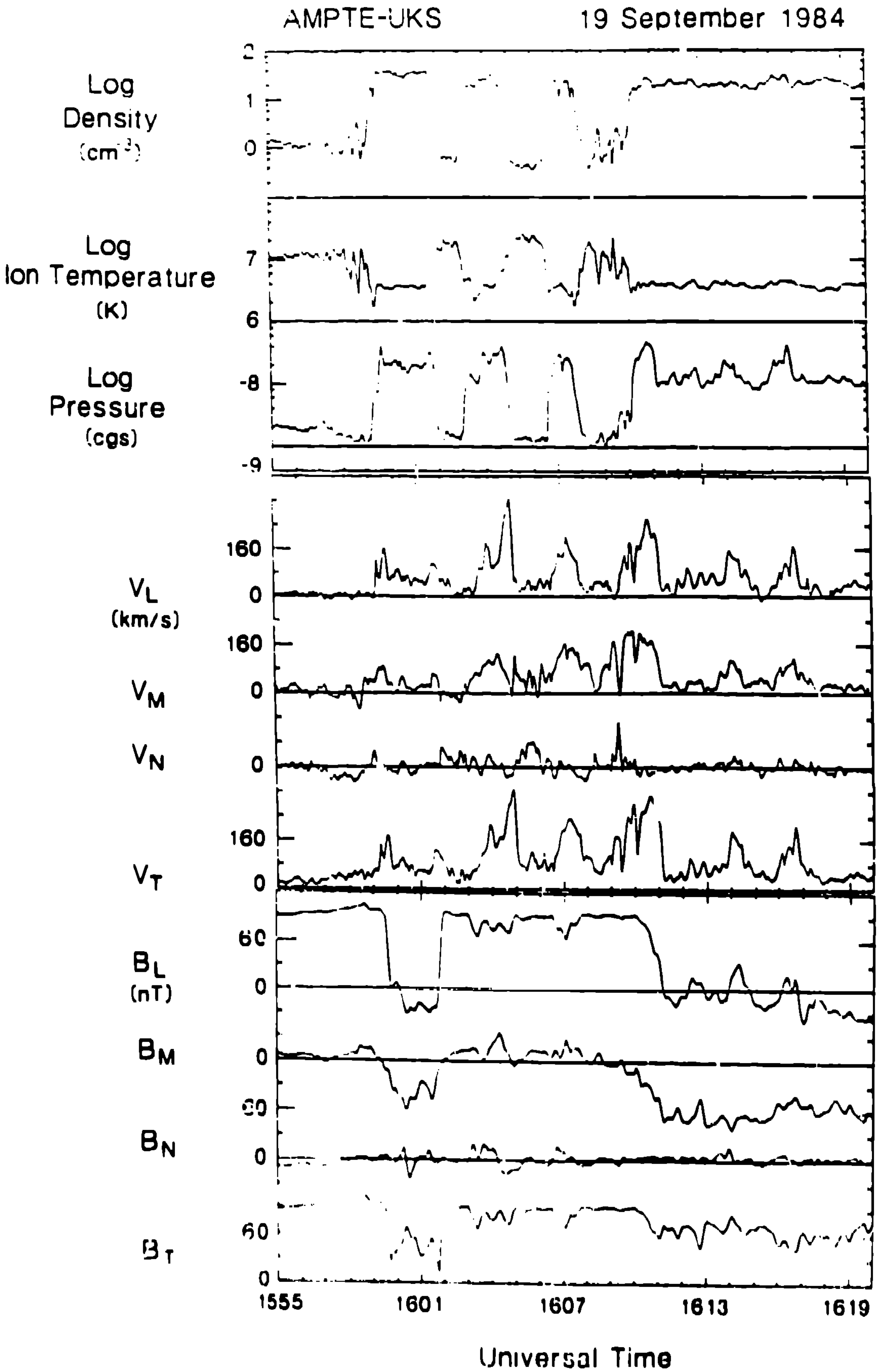
ISEE 1/2
Nov. 12. 1977
LMN
B_L
B_M
B_N
B_T (nT)
ΔB_L
ΔB_M
ΔB_N
ΔB_T (nT)
(1 - 2)
2257
2258
2259
2300
2301
Universal Time



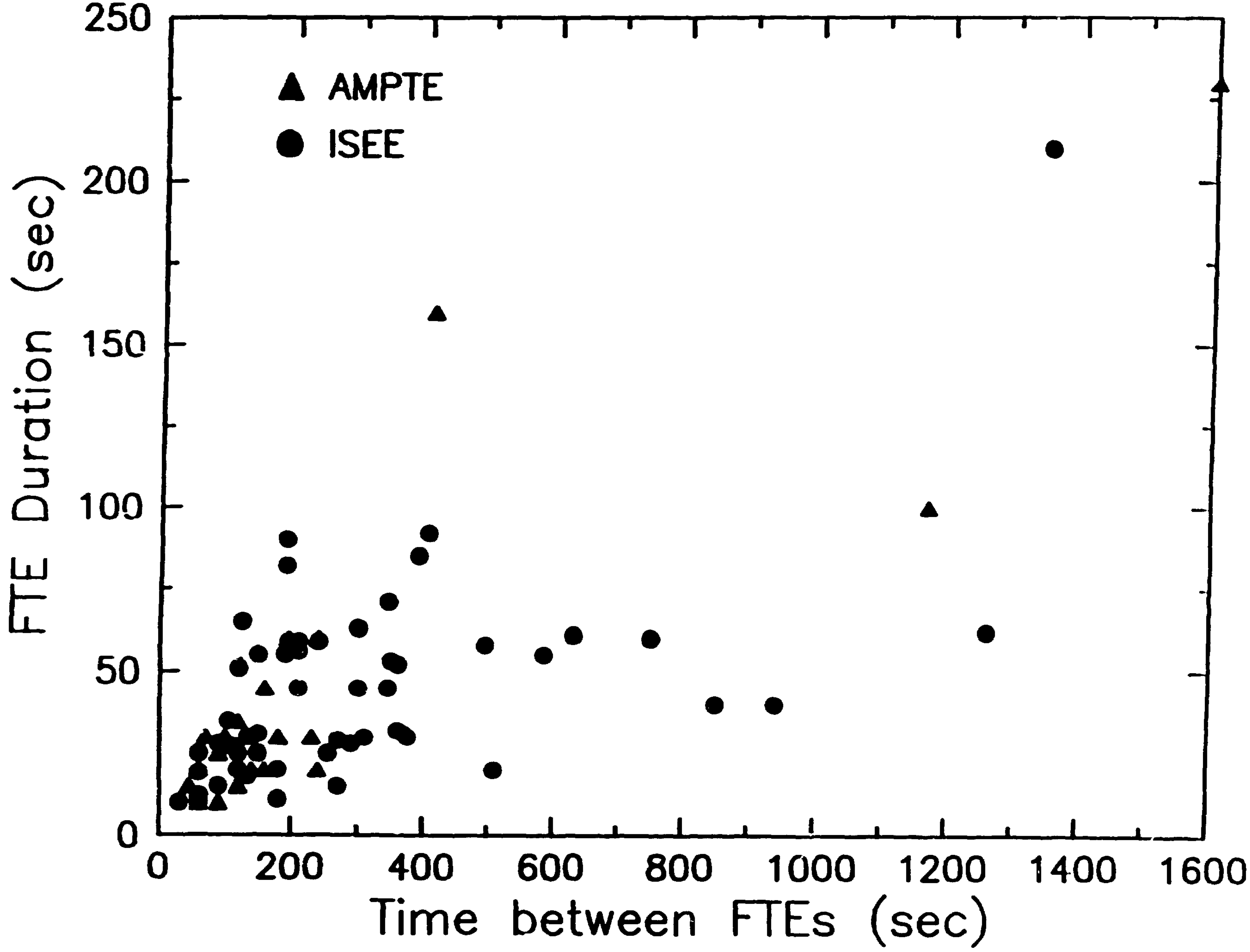
ISEE 1 ORBIT 135 OUTBOUND 8 SEP 1978
Np
N̄p
10
1
0.1
0.01
RC
BL
MP
MS
MP
MS
S
Vp
350
250
150
Vz
+300
+100
-100
-300
GSM
Bz
+30
+10
-10
-30
GSM
P
B
1
60
30
UT 00:23 29 35 41 47 53 00:59
R 7.997 8.913
ISEE 2
Np
N̄p
10
1
0.1
0.01
MP
S
MS
S
Vp
350
250
150
Bz
+30
+10
-10
-30
GSM
UT 00:23 29 35 41 47 53 00:59
R 8.302 9.195

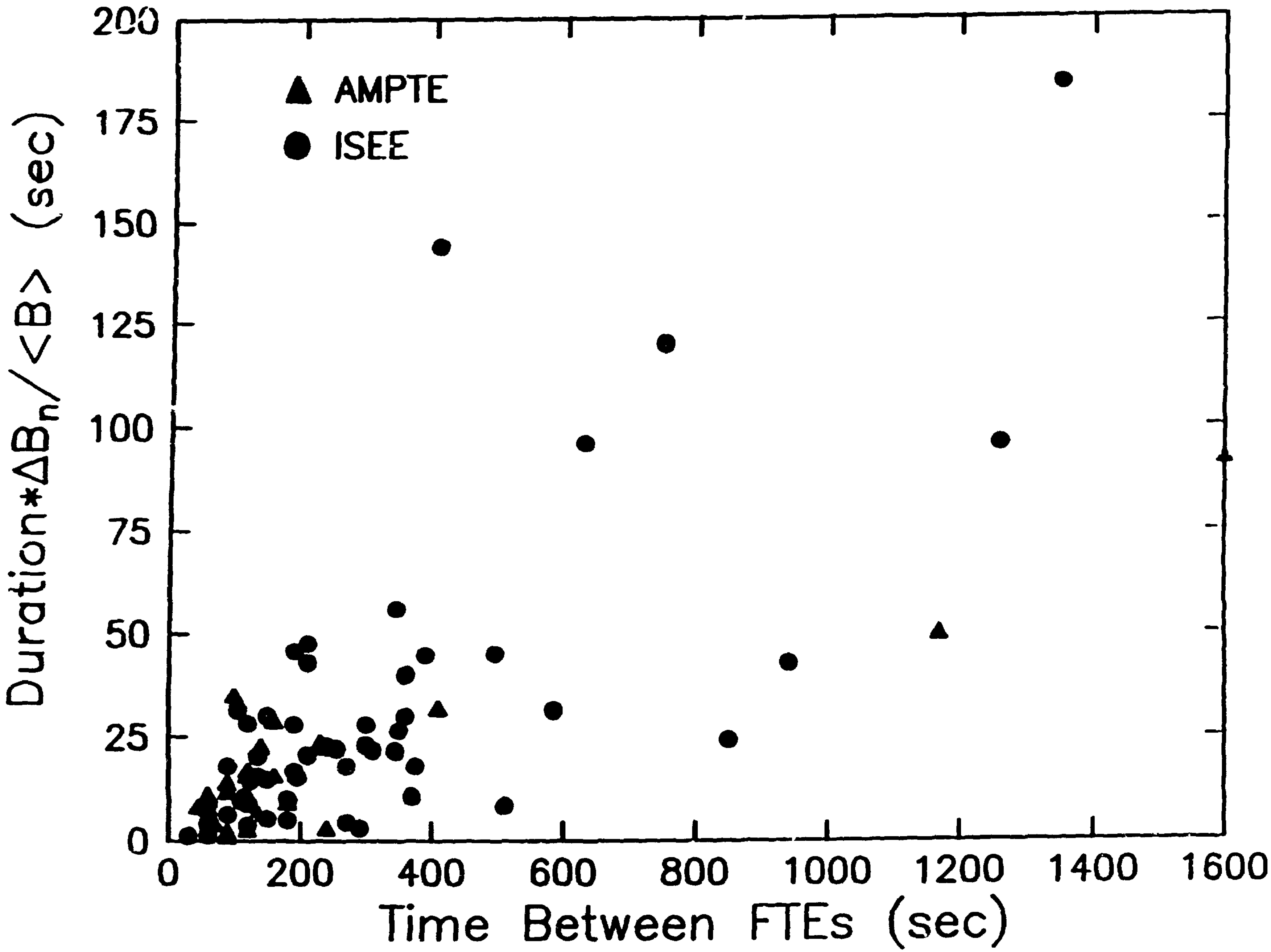


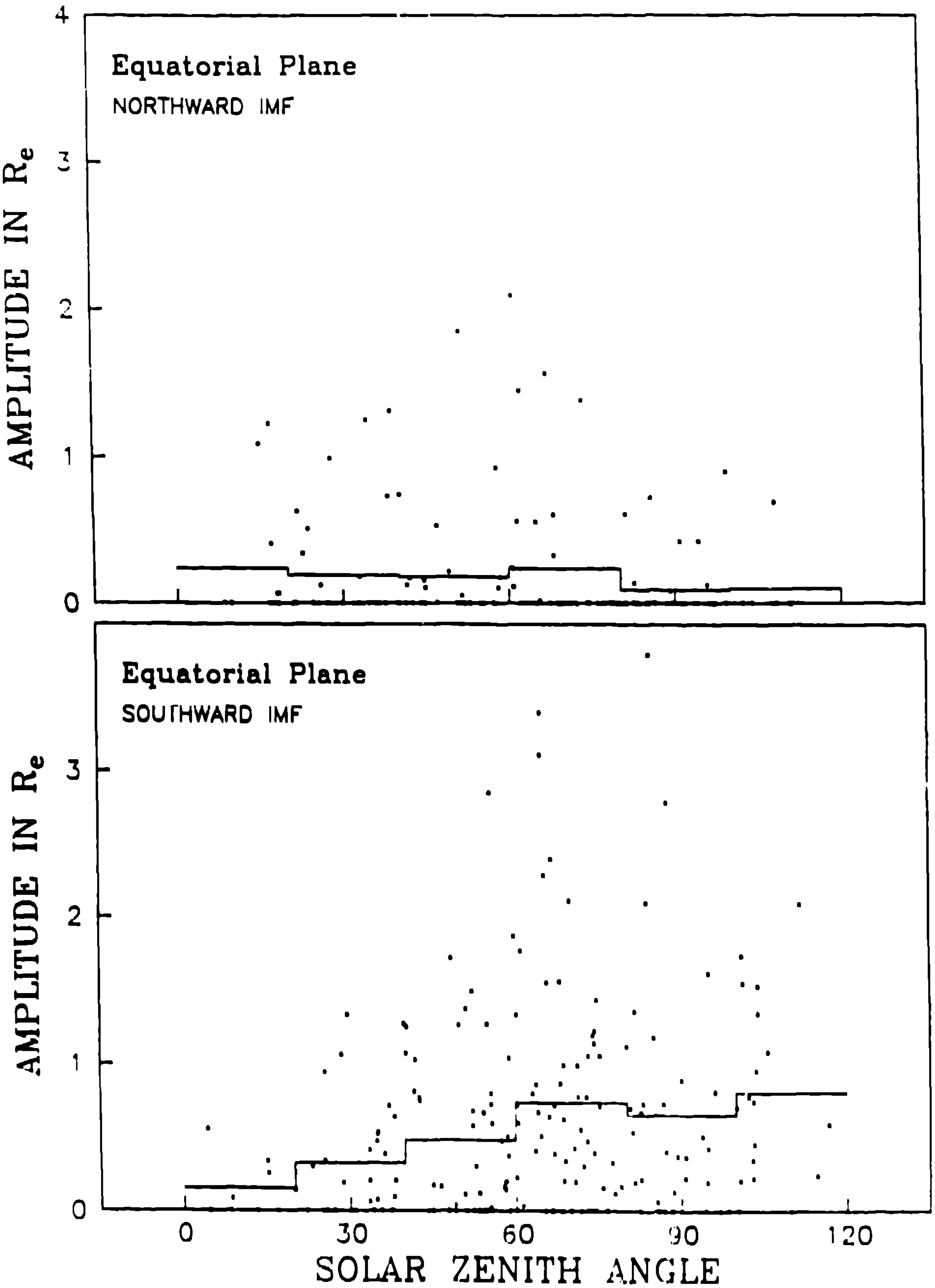
ISEE-2
October 21, 1980
B_L
B_M
B_N
IBI
(nT)
60
30
0
-30
1200
1210
1220
1230
1240
1250
1300
1310
1320
1330
1340
Universal Time



AMPTE-UKS
19 September 1984
Log Density (cm⁻³)
2
1
0
Log Ion Temperature (K)
7
6
Log Pressure (cgs)
-8
-9
160
V_L (km/s)
0
160
V_M
0
V_N
0
160
V_T
0
60
B_L (nT)
0
B_M
0
60
B_N
0
60
B_T
0
1555
1601
1607
1613
1619
Universal Time


AMPTE
ISEE
FTE Duration (sec)
Time between FTEs (sec)
0
50
100
150
200
250
0
200
400
600
800
1000
1200
1400
1600


AMPTE
ISEE
Duration*ΔB_n/<B> (sec)
Time Between FTEs (sec)
0
25
50
75
100
125
150
175
200
0
200
400
600
800
1000
1200
1400
1600


Equatorial Plane
NORTHWARD IMF
AMPLITUDE IN R_e
4
3
2
1
0
Equatorial Plane
SOUTHWARD IMF
AMPLITUDE IN R_e
3
2
1
0
0
30
60
90
120
SOLAR ZENITH ANGLE